



Na-NiCl₂ batteries

Christensen, Rune

Published in:
Technology Data for Energy storage

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Christensen, R. (2018). Na-NiCl₂ batteries. In *Technology Data for Energy storage: November 2018* (pp. 147-160). [183] Danish Energy Agency. <https://ens.dk/en/our-services/projections-and-models/technology-data>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

183 NA-NICL₂ BATTERIES

Contact information:

Danish Energy Agency: Thomas Mandal Østergaard , tmo@ens.dk

Energinet.dk: Rune Duban Grandal, rdg@energinet.dk

Author: Rune Christensen (runch@dtu.dk), DTU Energy

Publication date

December 2018

Amendments after publication date

| Date | Ref. | Description |
|------|------|-------------|
| | | |

Brief technology description

Na-NiCl₂, or Sodium-nickel chloride, batteries are secondary (i.e. rechargeable) batteries. They are also known as ZEBRA (Zeolite Battery Research Africa Project) batteries. They are applicable for both power-intensive and energy-intensive electrical energy storage. They can be used on both grid level and for mobile applications such as electric and hybrid vehicles [1].

Na-NiCl₂ batteries are similar to the more mature Na-S batteries. The key components of a Na-NiCl₂ battery cell are the molten sodium anode, a ceramic β -alumina oxide solid state electrolyte (BASE), and a porous cathode, where the reactant is NiCl₂. The cathode also contains liquid NaAlCl₄ to obtain sufficient ionic conductivity [2], [3]. A schematic of a cell can be seen in Figure 1.

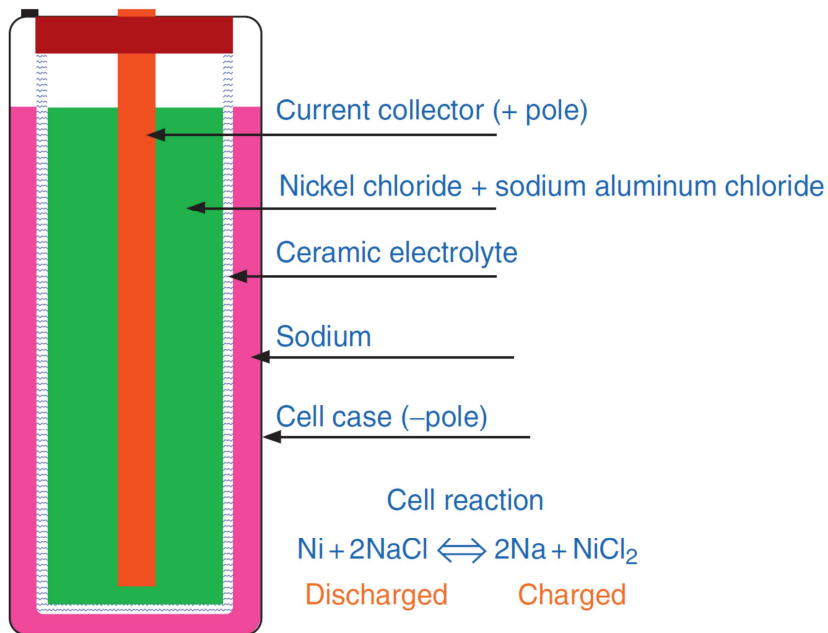


Figure 1: Schematic of Na-NiCl₂ battery cell. The “Ceramic electrolyte” is BASE [1].

A picture of five connected cells and the components used to manufacture a cell can be seen in Figure 2.

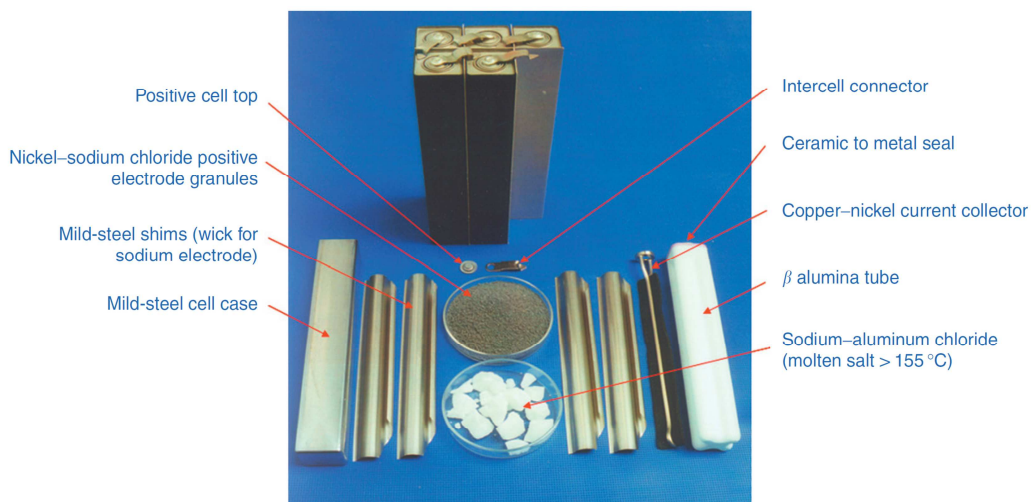
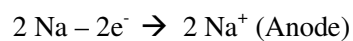
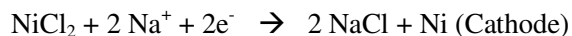


Figure 2: Na-NiCl₂ battery cell components [1].

Cells are assembled in a fully discharged state. This allows the sodium to be supplied in the form of NaCl as can be seen from the discharge reaction:





During charge the reverse reaction occurs. The reaction has a full cell potential of 2.58 V at 300 °C. The operating temperature is 250 °C to 350 °C to ensure sufficient Na ionic conductivity through the BASE [4]. A lower limit operation temperature of 150 °C is required to maintain liquid NaAlCl_4 [1]. An illustration of the charging reaction can be seen in Figure 3.

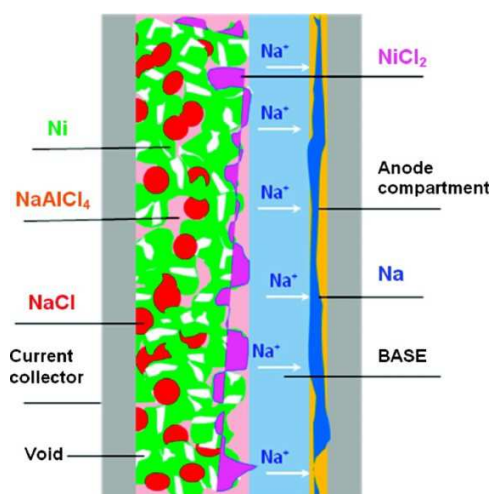


Figure 3: Illustration of Na-NiCl₂ charging process [2].

The battery cells are connected in battery units with thermal insulation, heating and cooling systems, and various control systems. Battery modules can be combined in larger battery units for grid scale applications. Current commercial grid scale units are shown in Section “Examples of market standard technology”. A grid scale Na-NiCl₂ battery installation consists as a minimum of a unit containing the battery modules, a battery management system, and a power conversion system required to connect the batteries to the grid.

For a more detailed technology description the reader is referred to “Encyclopedia of Electrochemical Power Sources” [1].

Input/output

The primary input and output are both electricity. Electricity is converted to electrochemical energy during charge. The electrochemical energy is converted back to electricity during discharge in the reaction process described above.

Energy efficiency and losses

Heat loss is reported to be less than 0.6 % of total energy storage capacity per hours for a 17.8 kWh battery module and less than 0.3 % of total storage capacity per hour for a 35.7 kWh battery module [1]. The heat loss depends on the specific assembly unit. Heat loss in large battery installations consisting on multiple assembly

units, e.g., 10 identical container assembly units, each containing multiple battery modules is expected to scale approximately linearly with installation size. The heat loss in percentage of total energy storage capacity is thus approximately independent of total installation size. During continued operation, which can include some hours of idle time, the Ohmic losses in the charge/discharge reaction will balance the heat loss. The heat loss should thus not be treated as an independent source of energy loss during operation as it is included in the battery efficiency. Simple air cooling is sufficient for maintaining temperature during operation and build into standard battery units.

Na-NiCl₂ batteries can be repeatedly cooled to ambient temperatures and reheated, i.e. undergo so-called freeze-thaw cycles, without any decrease to battery lifetime [1], [4], [5]. Typical time scales are days to solidify during cooling and tens of hours to liquidize during reheating [6]. Na-NiCl₂ batteries should remain heated during shorter idle periods.

At grid scale battery operation, the DC efficiency of a Na-NiCl₂ module has been measured to 90 % [7]. A 0.5 MW Na-NiCl₂ battery unit has been measured to 89 % [4]. Auxiliary losses, e.g., from cooling account for approximately 2 % [7].

Regulation ability and other system services

Standard recharging is slower than discharging the battery, i.e. the standard charging input will be lower than the rated output capacity. Commercial data states 6-8 hours to recharge a battery with 3 hour capacity at rated discharge capacity [1], [8]. Fast recharge at a rated equal to or above the rated output power is possible at the cost of decreased energy efficiency and accelerated battery degradation [9]. At low charge/discharge rates (approximately 1/3 of rated power) the full battery energy storage capacity can be used. At rated power output only 80 % of storage capacity should be utilized to prevent accelerated degradation [4].

The response time (i.e. the time it takes for the battery to supply requested charge or discharge power) is stated to be 20 ms [10] and measured to be less than 1 second when the battery is operational [4]. The response time from non-operational mode with the battery at operating temperature takes 45 seconds. [4].

Given the necessary power conversion system (PCS) equipment etc. is installed, Na-NiCl₂ batteries are able to provide energy pulses of up to at least 3 times rated power capacity for periods measured as long as 30 min but with storage capacity reduced by a factor of two compared to rated discharge rate [4]. The effect of such operation on battery lifetime is not known.

Grid scale battery operation depends on the application. Batteries used for time shifting will generally complete a single charge/discharge cycle over 24 hours. Batteries used for various other grid services including stabilization of input from renewables will often not undergo traditional battery cycling but frequently switch between being charged and discharged according to demand.

Na-NiCl₂ batteries can provide a range of system services. The manufacturer FZSoNick states the following applications: Load levelling, power quality, renewable resource optimization, and utility grid ancillary services [8].

Typical characteristics and capacities

Some noteworthy European stationary installations of Na-NiCl₂ batteries are listed in Table 1.

| Name | Location | Year of commissioning | Storage capacity | Rated power output capacity |
|--|---|-----------------------|----------------------------------|-------------------------------|
| FIAMM Green Energy Island | Almisano, Italy | 2010 | 230 kWh | 180 kW |
| EDF EN Gabardone Project | Colombiers, France | 2013 | 70 kWh | 20 kW |
| Terna Storage Lab 1+2 (3 installations) | Codrangianos (Sardinia) and Ciminna (Sicily), Italy | 2014 and 2015 | 4150 kWh 2000 kWh 4150 kWh | 1200 kW 1000 kW 1200 kW |

Table 1: Selected Na-NiCl installations in Europe [4], [11], [12].

The energy density and specific energy calculated for the Energy Spring 164 system from FZSoNick [8] (See Figure 5) is 32.8 kWh/m³ and 56 Wh/kg, respectively.

Typical storage period

The storage period for Na-NiCl₂ batteries depends on the operation of the batteries and can range from minutes to hours.

Space Requirement

For the Energy Spring 164 system from FZSoNick [8], the footprint of a single battery assembly unit is 10.5 m²/MWh. Data is not available for footprint of full installations of Na-NiCl₂ batteries. Assuming Na-NiCl₂ battery assembly units will occupy a similar fraction of total installation area as Na-S battery units, the total installation footprint can be estimated to 70 – 116 m²/MWh on the basis of large recent Na-S battery installations [13]–[15]. This estimate takes into consideration that the battery unit footprint is 1.5 times larger per MWh for current commercially available Na-NiCl₂ battery units than commercially available Na-S battery units (See Figure 5 and reference [16]).

Advantages/disadvantages

General advantages and disadvantages of batteries in comparison to other technologies for energy storage are listed in Table 3.

| Advantages | Disadvantages |
|----------------------------|---------------------------|
| Short response time | |
| Flexible installation size | Relatively short lifetime |
| High energy efficiency | |
| Versatile application | Large investment cost |
| Relatively compact | |
| Low maintenance | |

Table 3: General advantages and disadvantages of batteries in comparison to other technologies for energy storage

Even compared to other batteries, Na-NiCl₂ batteries are considered reliable and low maintenance [8], [17]. Na-NiCl₂ are high temperature batteries, however they can operate at lower temperatures than Na-S batteries. They can in contrast to Na-S batteries withstand repeated cooling and reheating without degradation [4], [5]. They have significant pulse power capabilities, i.e. they can operate at higher power than rated for short durations of time [18][19]. They are among the most efficient large scale batteries. They are, despite the highly reactive molten sodium electrode and elevated temperatures, considered relatively safe due to intrinsic safety features [4], [18], [20].

The batteries are currently expensive compared to other batteries for grid scale application for both energy intensive and power intensive applications. There is currently only one trading manufacturer. The energy storage capacity is directly coupled to the usage of nickel, which account for 47% [21] to 60 % [22] of raw material costs. The raw material cost of nickel is approximately 18 \$/kWh at a price of 11.6 \$/kg [21]–[23]. Cost of Ni is currently not critical to the overall battery cost but could become significant in case of large production cost reductions.

Environment

Operating batteries contain molten sodium, which pose a potential safety and environmental risks. Risk analyses can be found in References [4], [20]. Raw materials used in the production of Na-NiCl₂ batteries are nonhazardous and globally available [20]. Discharged batteries can easily be recycled and the nickel reclaimed [17], [20]. A detailed Life Cycle Assessment (LCA) can be found in Reference [24].

Research and development perspectives

It is not possible to quantify the full potential for improvements through R&D at the given time. The potential is however, estimated to be substantial in terms of both technical and financial specifications [25].

All critical components of the battery are undergoing active research. These include the BASE, the sealing materials, the sodium electrode, the cathode, and battery interfaces. Research efforts are especially focused on geometry optimizations and improvement of Na ionic conductivity through the BASE. New solid electrolytes to replace BASE are also being considered [25].

Research is also going into slightly changed chemistries which would change the battery characteristics significantly [3], [26].

Due to the similarity with Na-S batteries, synergies in research and development efforts can be expected.

Examples of market standard technology

FZSoNick, a subsidiary of FIAMM, is the only currently trading commercial manufacturer of Na-NiCl₂ batteries [8]. Illustration and technical specifications available at below referenced URL are presented for a grid scale assembly unit in Figure 4 - Figure 5. Units are highly modular and can be combined to an installation of desired size.



Figure 4: Energy Spring 164 system from FZSoNick [8].

Energy Spring 164 Technical Specification for configuration of 64 ST523

| | |
|--|--|
| Battery / Chemistry Type | NaNiCl ₂ |
| Constant Power Discharge (Rated) | 400 kW for 3 hours |
| Nominal Energy Capacity | 1.4 MWh (100% DOD) |
| System Rating (Voltage, Current Capacity) | Nom. 620 VDC, Nom. 2432 Ah |
| Min / Max Operative System Voltages | 500 VDC / 700 VDC |
| Standard Charge / Discharge hours | 8 hours of charge, 3 hours of discharge |
| Standard Circuit Design | Up to 64 battery modules connected in parallel |
| Enclosure Dimensions | L: 6058 mm / 238.5 in H: 2896 mm / 114 in W: 2438 mm / 96 in |
| Weight (metric ton) | 25 t (with battery modules), 10 t (without battery modules) |
| Heater Consumption during floating | <10 kW |
| Ventilation | Not need Air Conditioning, only forced-air ventilation for power electronics |
| Design Cycle Life | 4500 Cycles at 80% DOD |
| Product / Material Specifications | Please refer to ST523 battery specifications |
| BMS Characteristics | Please refer to ST523 battery specifications |

Figure 5: Specifications for Energy Spring 164 system from FZSoNick [8]. http://www.fzsonick.com/media/369733/20161221_energy-spring-164_datasheet-a4.pdf

Prediction of performance and cost

Data for 2015

The Italian “Terna Storage Lab” installation reported above has been used for economic data to as large extend as possible [4], [12]. A significant reason for placing emphasis on this specific installation is that the owner, Italian grid operator Terna, has made financial and measured technical data available. This is preferred over estimates.

The balance between power capacity and energy storage capacity in battery installations will influence the investment costs per MW and MWh. The ratio can be quantified through the discharge time at rated power, h , and has historically varied. Calculated as a weighted average for the “Terna Storage Lab”, h is 3 hours. This is similar to h for currently available commercial grid-scale units.

O&M costs are obtained from Carlsson et al. [27] (assumed similar to 2013 values for Na-S batteries in good agreement with EPRI data [28]), and Zakeri and Syri [29]. It is highly uncertain how O&M costs will change in the future with deployment of highly standardized container type units.

Assumptions for the period 2020 to 2050

Estimates for 2020 and 2030 in the data sheet below are based on data from IRENA [30]–[32]. Values in USD have been converted to € using an exchange rate of 0.86.

As discussed in the Chapter Electricity Storage, the current PCS cost including grid connection is 0.4-0,5 M€/MW. This is used as reference value for the “capacity component”. The inverter costs, which account for approximately 50 % of cost [13], [22], [24], is predicted to decrease by 20 % in 2020 and 50 % in 2030 [25], [26]. The other 50 % of cost is assumed constant. Cost reductions of capacity components is assumed to not occur beyond 2030.

2050 values of the battery cost (here “energy component”) predicted from learning curves have previously found cost reductions of approximately 10 % [23] and 25 % [28] for the period 2030 to 2050 for Na-S batteries. As Na-S and Na-NiCl₂ batteries have similar cost drivers, the average (17.5 %) is used for the energy component cost in 2050.

“Other project costs” is assumed to be 8 % of CAPEX (here “Specific investment”), as was the case for the Terna unit [29].

O&M costs are assumed to be constant in the given units.

No development in calendar lifetime, cycle lifetime, and efficiency is assumed to take place beyond 2030. The regulatory ability is assumed to not improve.

Learning curves and technological maturity

The level of maturity for grid scale Na-NiCl₂ batteries is “Category 2: Pioneer Phase”. Based on the current commercial situation it is not possible to establish learning curves. The technology is for grid scale applications suffering from slow rate of deployment compared to other grid scale batteries despite being relatively old. It is doubtful whether grid scale Na-NiCl₂ batteries will ever achieve Category 3 maturity: “Commercial technologies with moderate deployment”.

Uncertainty

As the technology is in Category 2 level maturity, a technology development track cannot yet be established without large uncertainty. Uncertainties for 2020 and 2030 are when possible obtained from IRENA [26], [27]. Uncertainties in 2050 are assumed to be percentagewise similar to those in 2030. For the “capacity component” the maximum values for PCS cost found by Zakeri and Syri [24] are used as baseline. The uncertainties are calculated for future years by keeping the relative uncertainty compared to the cost prediction constant.

The uncertainties for O&M costs are determined using the literature review by Zakeri and Syri [24]. The uncertainties are calculated from the expected value using the relative difference between the extrema and the average in the literature review. Uncertainties are in general large.

Additional remarks

Since battery units are highly modular and equipment is the main cost of a full installation, a close to linear scaling in total cost vs. installation size is expected from a technological point of view. Significant financial benefits from increasing installation sizes will rely on negotiations with the manufacturer.

Even though Na-NiCl₂ batteries have high commercial potential, rapid cost reduction of alternative storage solutions, e.g. Li-ion batteries could halt commercial deployment and technological development of Na-NiCl₂ batteries. This can prevent Na-NiCl₂ batteries from reaching full commercial potential.

Quantitative description

Assumptions for prediction of development are discussed above.

| Technology | Na-NiCl ₂ battery | | | | | | | | | |
|--|-------------------------------------|-------|-------|-------|--------------------|--------------------|-------|-------|-------|-------------------------|
| | 2015 | 2020 | 2030 | 2050 | Uncertainty (2020) | Uncertainty (2050) | Note | Ref | | |
| Energy/technical data | Lower | | Upper | | Lower | Upper | | | | |
| Form of energy stored | Electricity | | | | | | | | | |
| Application | System, power- and energy-intensive | | | | | | | | | |
| Energy storage capacity for one unit (MWh) | 4.15 | 4.15 | 4.15 | 4.15 | 3.11 | 5.19 | 3.11 | 5.19 | A,B,P | [12]+[11] |
| Output capacity for one unit (MW) | 1.2 | 1.2 | 1.2 | 1.2 | 0.90 | 1.50 | 0.90 | 1.50 | A,B,P | [12]+[11] |
| Input capacity for one unit (MW) | 0.45 | 0.45 | 0.45 | 0.45 | 0.34 | 0.56 | 0.34 | 0.56 | C,P | [34]+[8] |
| Round trip efficiency DC(%) | 87 | 87 | 87 | 87 | 81 | 93 | 83 | 95 | D | [4]+[7]; [31] |
| - Charge efficiency (%) | - | - | - | - | - | - | - | - | | |
| - Discharge efficiency (%) | - | - | - | - | - | - | - | - | | |
| Energy losses during storage (%/day) | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 15 | E,P | [35]+[5];[31] |
| Forced outage (%) | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | F,P | [8] |
| Planned outage (weeks per year) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F,P | [8] |
| Technical lifetime (years) | 15 | 17 | 23 | 23 | 9 | 25 | 12 | 33 | | [28]+[8];[30]+[32]+[31] |
| Construction time (years) | 0.5 | 0.5 | 0.5 | 0.5 | 0.2 | 2.0 | 0.2 | 2.0 | G,P | [11] |
| | | | | | | | | | | |
| Regulation ability | | | | | | | | | | |
| Response time from idle to full-rated discharge (sec) | 0.02 | 0.02 | 0.02 | 0.02 | 0.001 | 0.02 | 0.001 | 0.02 | | [10]/[4]+[33] |
| Response time from full-rated charge to full-rated discharge (sec) | 0.5 | 0.5 | 0.5 | 0.5 | 0.001 | 0.5 | 0.001 | 0.5 | H,P | [4] |
| | | | | | | | | | | |
| Financial data | | | | | | | | | | |
| Specific investment (M€2015 per MWh) | 1.0 | 0.42 | 0.26 | 0.23 | 0.32 | 0.53 | 0.18 | 0.30 | I, J | [12]+[28]; [30]+[31] |
| - energy component (M€/MWh) | 0.76 | 0.26 | 0.14 | 0.11 | 0.21 | 0.32 | 0.09 | 0.14 | K | [12]; [31] |
| - capacity component (M€/MW) | 0.48 | 0.41 | 0.33 | 0.33 | 0.30 | 0.58 | 0.25 | 0.47 | L | [12]; [31] |
| - other project costs (M€/MWh) | 0.08 | 0.03 | 0.02 | 0.02 | 0.03 | 0.04 | 0.01 | 0.02 | | [12] |
| Fixed O&M (% total investment) | 1.5 | 1.5 | 1.5 | 1.5 | 0.9 | 2.0 | 0.9 | 2.0 | M | [29]+[28]+[27] |
| Variable O&M (€2015/MWh) | 0.6 | 0.6 | 0.6 | 0.6 | 0.4 | 2.1 | 0.4 | 2.1 | N | [29] |
| | | | | | | | | | | |
| Technology specific data | | | | | | | | | | |
| Alternative Investment cost (M€2015/MW) | 3.0 | 1.4 | 0.9 | 0.8 | 1.1 | 1.8 | 0.6 | 1.0 | I | [12]+[28] |
| Lifetime in total number of cycles | 4500 | 4500 | 4500 | 4500 | 1500 | 11300 | 1500 | 11300 | O | [4]+[8];[30]+[32] |
| Specific power (W/kg) | 16 | 16 | 16 | 16 | 12 | 20 | 12 | 20 | O,P | [8] |
| Power density (W/m3) | 9350 | 9350 | 9350 | 9350 | 7012 | 11687 | 7012 | 11687 | O,P | [8] |
| Specific energy (Wh/kg) | 56 | 56 | 56 | 56 | 42 | 70 | 42 | 70 | O,P | [3] |
| Energy density (Wh/m3) | 32700 | 32700 | 32700 | 32700 | 24525 | 40875 | 24525 | 40875 | O,P | [3] |

- A. Italian batteries (Codrongianos (Sardinia) and Ciminna (Sicily)) used as standard.
- B. Highly modular technology type with near linear scaling between total cost and installation size. Power and storage capacity cannot be varied independently.
- C. Can fast recharge with rate identical to discharge rate. Standard charge/discharge time is 8/3 h.
- D. Efficiency varies depending on use. Loss due to balance of system is approximately 2 % higher than for Li-ion batteries with similar PCS equipment [7]
- E. During intended continuous operation, Ohmic losses maintain the temperature of the battery. Losses are thus included in round trip efficiency. No electrical self-discharge. Heat losses during idle periods on the order of 0.5 %/h discussed above. IRENA finds self-discharge per day to vary between 0.1 % and 15 % depending on unit and use [31]
- F. Highly reliable and with no downtime required for maintenance during lifetime according to manufacturer.
- G. Can be down to 2 months.
- H. Measurement. Possibly limited by PCS.
- I. Average value for Italian “Terna Storage Lab” batteries with their specific storage to power capacity ratio.
- J. Development rates from IRENA are used for prediction of future cost [30]
- K. Includes “Batteries” from reference [12]
- L. Includes “PCS-SCI”, “Transformer”, “Auxiliary equipment”, “Switching and actuating equipment”, and “System Controls & Instrumentation (SCI)” from reference [12].
- M. Assumed similar to Na-S batteries in good agreement with data from EPRI [28]
- N. Highly uncertain. Average value given. Reported in range 0.38 to 2.1 [29]
- O. Data for Energy Spring 164 system from FZSoNick. Irena do not expected improvements on cell level. Improvements on installation level might occur [32]
- P. Uncertainties are based on a qualified guess.

References

- [1] J. L. Sudworth and R. C. Galloway, "SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS | Sodium–Nickel Chloride," in *Encyclopedia of Electrochemical Power Sources*, 2009, pp. 312–323.
- [2] Z. Yang et al., "Electrochemical Energy Storage for Green Grid," *Chem. Rev.*, vol. 111, no. 5, pp. 3577–3613, May 2011.
- [3] X. Lu, G. Li, J. Y. Kim, J. P. Lemmon, V. L. Sprenkle, and Z. Yang, "A novel low-cost sodium–zinc chloride battery," *Energy Environ. Sci.*, vol. 6, no. 6, p. 1837, 2013.
- [4] R. Benato et al., "Sodium nickel chloride battery technology for large-scale stationary storage in the high voltage network," *J. Power Sources*, vol. 293, pp. 127–136, 2015.
- [5] G. L. Soloveichik, "Battery Technologies for Large-Scale Stationary Energy Storage," *Annu. Rev. Chem. Biomol. Eng.*, vol. 2, pp. 503–27, 2011.
- [6] B. Parkhideh, "Project : Storage Technologies for Hybrid Electric Buses - Subject : ZEBRA Battery," 2006.
- [7] M. Pietrucci, "Progetti Pilota Power Intensive: Descrizione degli impianti e delle tecnologie," 2017.
- [8] FZSoNick, "DATASHEETS," 2017. [Online]. Available: <http://www.fzsonick.com/en/emea/energy-storage/prodotti/spring,-mod-164,-324.aspx>.
- [9] M. Hosseinifar and A. Petric, "Effect of High Charge Rate on Cycle Life of ZEBRA (Na/NiCl₂) Cells," *J. Electrochem. Soc.*, vol. 163, no. 7, pp. A1226–A1231, 2016.
- [10] T. V Rachel Carnegie Douglas Gotham David Nderitu Paul Preckel, "Utility Scale Energy Storage Systems," 2013.
- [11] "DOE Global Energy Storage Database." [Online]. Available: <https://www.energystorageexchange.org/>. [Accessed: 29-Mar-2017].
- [12] R. Benato, G. Bruno, F. Palone, R. Polito, and M. Rebolini, "Large-Scale Electrochemical Energy Storage in High Voltage Grids: Overview of the Italian Experience," *Energies*, vol. 10, no. 1, p. 108, Jan. 2017.
- [13] NGK Insulators LTD, "Case Studies." pp. 1–13, 2016.
- [14] NGK Insulators LTD, "The World's Largest NAS Battery Installation Commences Operation Short Installation Period Achieved through Containerized, Compact Format," 2016. [Online]. Available: <http://www.ngk.co.jp/english/news/2016/0303.html>.
- [15] M. Andriollo et al., "Energy intensive electrochemical storage in Italy: 34.8 MW sodium-sulphur secondary cells," *J. Energy Storage*, vol. 5, pp. 146–155, Feb. 2016.
- [16] NGK Insulators LTD, "Structure of NAS Energy Storage System," 2016. [Online]. Available: <https://www.ngk.co.jp/nas/specs/>.
- [17] K. Bradbury, "Energy Storage Technology Review," *A Br. Introd. to Batter.*, no. September, pp. 1–33, 2010.

- [18] IEC, "Electrical Energy Storage," 2011.
- [19] A. Colthorpe, "NGK's NAS sodium sulfur grid-scale batteries in depth E," Energy Storage News, 2017.
- [20] C.-H. Dustmann and A. Bito, "SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS | Safety," in Encyclopedia of Electrochemical Power Sources, 2009, pp. 324–333.
- [21] R. C. Galloway, -Mes-Dea Sa, and C.-H. Dustmann, "ZEBRA Battery -Material Cost Availability and Recycling," vol. 1519, 2003.
- [22] H.-J. Chang, N. L. Canfield, K. Jung, V. L. Sprenkle, and G. Li, "Advanced Na-NiCl₂ Battery Using Nickel-Coated Graphite with Core– Shell Microarchitecture."
- [23] Fred Lambert, "Breakdown of raw materials in Tesla's batteries and possible bottlenecks | Electrek," Electrek, 2016. [Online]. Available: <https://electrek.co/2016/11/01/breakdown-raw-materials-tesla-batteries-possible-bottleneck/>. [Accessed: 12-Sep-2017].
- [24] S. Longo, V. Antonucci, M. Cellura, and M. Ferraro, "Life cycle assessment of storage systems: the case study of a sodium/nickel chloride battery," J. Clean. Prod., vol. 85, pp. 337–346, 2014.
- [25] O. Teller et al., "Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030," 2013.
- [26] X. Lu et al., "Liquid-metal electrode to enable ultra-low temperature sodium–beta alumina batteries for renewable energy storage," Nat. Commun., vol. 5, pp. 5884–5901, Aug. 2014.
- [27] J. E. Al Carlsson, "ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050," 2014.
- [28] G. Huff et al., "DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA," Rep. SAND2013- ..., no. July, p. 340, 2013.
- [29] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," Renew. Sustain. Energy Rev., vol. 42, pp. 569–596, 2015.
- [30] K.-P. Kairies, "Battery storage technology improvements and cost reductions to 2030: A Deep Dive," Int. Renew. Energy Agency Work., 2017.
- [31] IRENA, "Electricity storage and renewables: Costs and markets to 2030 - Cost-of-service tool. Version 1.0," 2017.
- [32] P. Ralon, M. Taylor, and A. Ilas, Electricity storage and renewables: costs and market to 2030, no. October. 2017.
- [33] L. Sigrist and E. Peirano, "E-Highway2050: Battery Storage Technology Assessment," in WP3 workshop April 15th, 2014.
- [34] J. Garche and C. K. Dyer, Encyclopedia of electrochemical power sources. Academic Press, 2009.
- [35] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," Prog. Nat. Sci., vol. 19, no. 3, pp. 291–312, 2009.